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Millimeter-band Surveys of Extragalactic Sources

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Abstract. Surveys at mm wavelengths emphasize rare classes of extragalactic radio sources characterized by spectra keeping flat or inverted up to high frequencies (such as blazars, GPS sources, advection dominated sources, or even gamma-ray burst afterglows), which are are difficult to single out at lower frequencies where the counts are dominated by far more numerous populations. Such surveys may lead to the discovery of populations with extreme properties, such as sources of the general GPS or blazar type but peaking at mm wavelengths, whose existence is hinted by currently available data. At relatively lower flux levels mm counts are dominated by high-redshift dusty galaxies, such as those detected by SCUBA and MAMBO surveys. These data have profound implications for our understanding of the formation and early evolution of galaxies. High sensitivity surveys at cm/mm wavelengths may also detect galaxy-scale Sunyaev-Zeldovich effects due to gas heated by central active nuclei.

1. Introduction

The millimeter region is quite a special one, since its corresponds to a minimum in the spectral energy distribution of the Galaxy and of most (but not all) classes of extragalactic sources. The minimum occurs at the cross-over between radio emission, which generally (but not always) decreases with frequency with a power law spectrum ($S_\nu \propto \nu^{-\alpha_r}$, with $\alpha_r \sim 0.5$ to 1), and dust emission which steeply rises with frequency (with a spectral index $\alpha_d \sim -3$ to -4). Just because of such steep rise the frequency of the minimum is only weakly dependent on the relative intensity of the two components. Moreover, the effect of redshift on the dust emission peak is to some extent compensated by the increase in dust temperature associated with the luminosity evolution of sources. This is why this

spectral band is optimal for mapping the Cosmic Microwave Background. For the same reason, it is also optimal for singling out the rare, but very interesting, source populations with non-standard spectra, which at other frequencies are submerged by the much more numerous populations with "standard" spectra.

In particular, the high-frequency selection allows us to beat the strong, free-free or synchrotron, self-absorption occurring in the densest emitting regions which are normally the closest to the central engine. As discussed in the following, this allows us to investigate both the earliest and the late phases of nuclear activity. But the millimeter region also carries key information on more conventional classes of radio sources and allows us to investigate the early phases of dust-obscured galaxy evolution.

2. Counts of extragalactic sources in the mm band

Our current best guess for integral counts at some mm wavelengths is shown in Fig. 1. At the brightest flux densities counts are dominated by radio sources. The counts shown here come from the model by [92] which reproduces quite well the statistics of sources at frequencies up to 8.4 GHz (see also [93]). Extrapolations to higher frequencies are liable to several sources of uncertainties: poorly known high frequency spectra, variability, appearance of classes of sources with poorly known space densities or whose very existence is not clearly established.

The inflection point, occurring at $\sim$ 1mJy for $\lambda = 3.3\,$mm and shifting to brighter (fainter) flux densities with decreasing (increasing) wavelength, signals the stepping in of a different population: dusty galaxies, characterized by very steep mm/sub-mm counts. Below $\sim$ 0.1mJy counts are well constrained by SCUBA and MAMBO surveys at $850\,\mu$m and 1.2 mm, respectively (Fig. 1). Above this flux density, we must resort to model predictions, which show a considerable latitude. Most current models actually predict much smoother counts in the transition region than those shown here. However, the model adopted here [41] appears to be, at the moment, the most astrophysically grounded. On the other hand, as discussed below, perhaps the transition is really smoother after all, although not for the reasons inherent in competing phenomenological models, but because of gravitational lensing, which introduces a significant tail, extending to $\sim$ 10 times brighter fluxes, of the counts of forming spheroidal galaxies, which, according to [41], dominate the SCUBA/MAMBO counts.

3. Radio sources

3.1. Sources with "standard" spectra

Let us focus first on the radio-source component. What is it made of? We know that most classes of sources fade away as we move to mm wavelengths: steep-spectrum sources tend to further steepen their spectra because of electron aging effects, but also it has long been known that only a fraction of sources with flat or rising spectra up to 5 GHz, keep them that way up to 90 GHz [62, 100]; many of them become optically thin, and therefore steep-spectrum, at mm wavelengths. Still, these populations are expected to comprise quite a significant fraction of sources detected at $\lesssim 1\,$cm so that surveys in this region

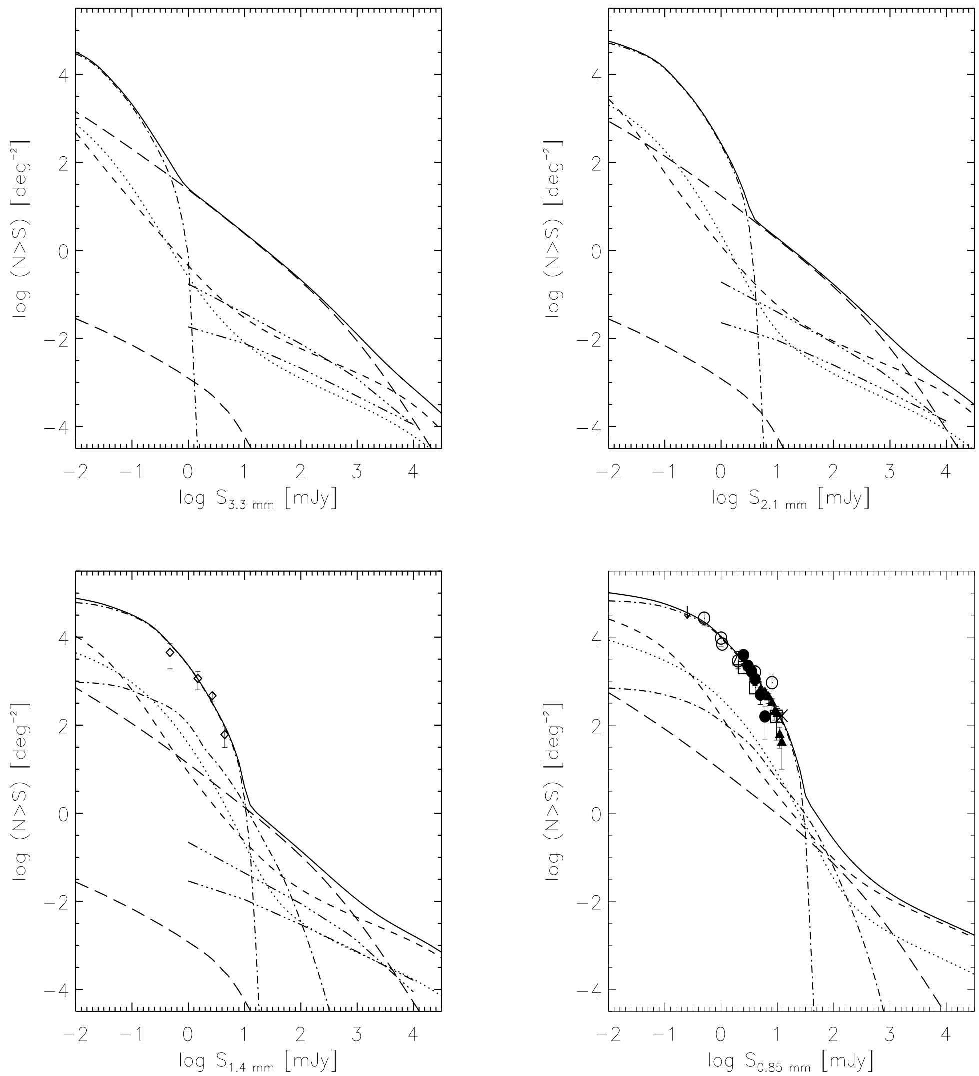

Figure 1. Expected integral counts of extragalactic sources at mm wavelengths. The solid lines show the sum of contributions from the various populations characterized by either dust emission (forming massive spheroidal galaxies: dot-dashed lines; spiral galaxies: short dashes; starburst galaxies: dotted) or by non-thermal synchrotron emission (standard steep- and flat-spectrum radio-galaxies: upper long-dashed lines; GPS sources with rest frame peak frequency, $\nu_{p,0}$, in the range 1–10 GHz, more numerous at fainter flux densities, and with $\nu_{p,0} > 10\,\mathrm{GHz}$: three dots-dashes; gamma-ray bursts: low dashed line, not shown at $850\,\mu$m). At 1.4 mm and $850\,\mu$m only we also show (second set of dot-dashed lines, lower at low flux densities but taking over at the brightest ones) the counts of strongly lensed forming spheroids. The data points are described in [70].

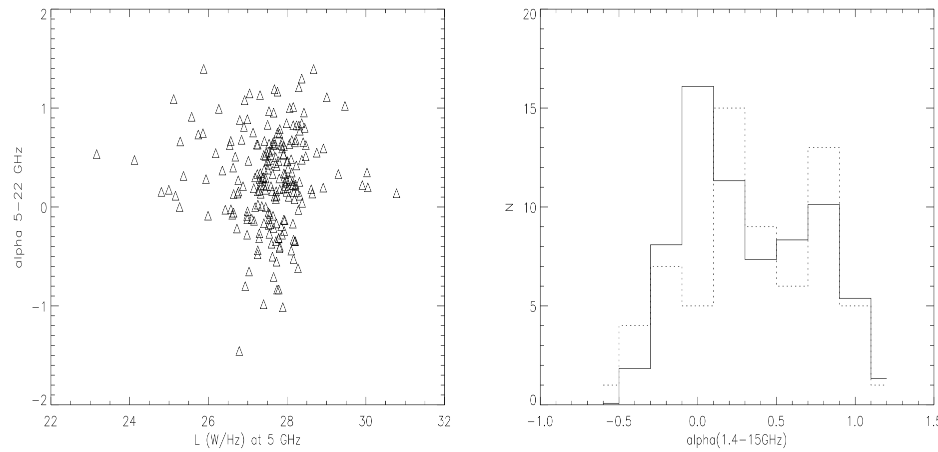

Figure 2. Observed (dotted) and fitted (solid) distribution of 1.4–15 GHz spectral indices for the sample by [89] (right-hand panel) and 5–22 GHz spectral index distribution of "flat"-spectrum ($\alpha_{1.4-5\mathrm{GHz}} < 0.5$) sources in Kühr's [49] sample for which 22 GHz measurements are available (left-hand panel).

will allow us to get very interesting information on their physical properties. For example, the distribution of spectral steepenings as a function of frequency provides statistical information on the distribution of radiative ages of sources and on mechanisms for injection and energy losses of relativistic electrons; the transition frequency from optically thick to optically thin synchrotron emission carries unique information on properties of the relativistic electron population and on the magnetic field strength of the most compact emitting regions.

The preliminary results of the survey at 15.2 GHz with the Ryle telescope [89] are already providing interesting hints. Current models [28, 92], that successfully account for the counts at frequencies up to 8.4 GHz (see [93]) overpredict the number of sources at the survey limit ($\simeq 20$ mJy) by a factor $\simeq 1.5$–2, implying that the simple assumptions adopted for source spectra break down. Preliminary results of a more detailed analysis (Ricci & De Zotti, in preparation) show that to account for both the 15 GHz counts and the corresponding spectral index distribution, significant constraints on spectral properties of both steep- and flat-spectrum sources must be introduced. A satisfactory fit is obtained by assuming an average steepening above 5 GHz by $\langle\delta\alpha\rangle \simeq 0.35$ of steep-spectrum sources ($\alpha_{1.4-5\mathrm{GHz}} > 0.5$) and, for sources with flatter 1.4–5 GHz spectra, a different distribution of high-frequency (5–22 GHz) spectral indices above and below $\log L_{5\,\mathrm{GHz}}(\mathrm{W/Hz}) = 26.5$. The model used in the right-hand side panel of Fig. 2 assumes that, below this limit, the spectral index distribution of sources with $\alpha_{1.4-5\mathrm{GHz}} < 0.5$ is a Gaussian with mean 0.49 and dispersion 0.41, while above this limit the distribution shown in the left-hand panel was used. For sources with $\alpha_{1.4-5\mathrm{GHz}} > 0.5$ a Gaussian distribution of spectral indices above 5 GHz was adopted, with mean 1.15 and dispersion 0.5.

3.2. Blazars

But mm-wave surveys will have an even greater impact on the study of the classes of sources with "non-standard" spectra, keeping flat or inverted ($\alpha \leq 0$) up to very high frequencies. The best known population of this kind are blazars.

Blazars are a composite population, with Spectral Energy Distributions (SEDs) characterized by two broad peaks, the synchrotron and the inverse Compton peak, which occur at widely different frequencies. They have also a sort of bimodal distribution of polarization properties. It is not yet clear whether there is a continuity or an evolutionary link between the various sub-populations, although some hints in this direction have been found (e.g. inverse correlation between luminosity and synchrotron peak frequency: [39, 35]).

With the better samples that can be obtained at mm wavelengths it should be possible to test the currently favoured theoretical paradigm, according to which the phenomenology of bright blazars can be accounted for by a sequence in the source power and intensity of the diffuse radiation field, surrounding the relativistic jet, which determines the distribution of synchrotron and inverse Compton peak frequencies. Millimetric data will therefore enable us to study the structure and the physics of radio jets.

Also, transition and extreme (mm peaking blazars), for which at the moment only some circumstantial evidence is available, should be discovered by mm surveys. For example, the two main discovery techniques, radio and X-ray selection, have produced two subclasses of BL Lac objects with different distributions of radio to X-ray luminosity ratios, X-ray selected ones being substantially weaker in the radio, although no evidence of a significant population of radio-silent BL Lacs has been found. It is not clear whether X-ray and radio selections sample the extremes of the distribution of the BL Lac population or they are discovering populations with different intrinsic properties. Millimetric surveys are optimal for identifying and systematically studying these sources, to assess whether there is continuity among the sub-classes and to investigate whether they fit within the framework of unified models. There are also hints that the radio to mm spectral indices of faint flat-spectrum sources tend to be steeper than those found for the brighter ones [95, 94]. These indications, and their interpretation, can only be tested and investigated with high frequency surveys.

Other very interesting open issues are the characterization of variability and polarization. Very compact sources are variable, with typical timescales limited to $\delta t > d/c$, where d is the source size and c is the velocity of light. In some cases the shape of the spectrum was also found to vary, hinting at evolutionary relationships between different classes of sources. A particularly hot issue is intra-day variability (IDV), which is most pronounced for flat-spectrum sources [97, 50]. Since interstellar scintillation, which is known to play a role in the observed cases of IDV, should not be important at mm wavelengths, measurements in this band would greatly help the physical interpretation of this phenomenon.

The dominant emission process for powerful radio sources is synchrotron whose radiation is intrinsically highly polarized. Yet the observed polarization degree of most sources observed at MHz or GHz frequencies is not higher than a few percent. The depolarization may be due either to random alignment of the

magnetic field in the source or to differential Faraday rotation of the emergent radiation. The latter effect scales as ν^{-2} and is therefore likely to be small at mm wavelengths. Therefore polarimetric measurements in this spectral region would allow us to measure the intrinsic polarization of sources and, together with polarization measurements at lower frequencies, to determine the Faraday depth. Note that the Doppler boosting of photon frequencies along the jet axis, invoked to explain the extreme brightness temperatures of compact sources, would make the observed polarization for these sources liable to Faraday rotation up to much higher frequencies than non Doppler-boosted sources.

It is worth noticing that thanks to Doppler boosting, very high redshift blazars can show up at relatively bright radio fluxes. In fact, several $z > 4$ blazars have been observed at flux density levels $\gtrsim 50$–$100\,\mathrm{mJy}$ ([82] and references therein). They are therefore convenient beacons for investigating the abundance of $\sim 10^9\,\mathrm{M}_\odot$ BHs and of their host galaxies at universe ages of about 1 Gyr and, in general, to explore the early phase of structure formation and the origin of the radio phenomenon. The maximum angle between the jet and the line of sight should be between 13.5 and 6.1 degrees, for the likely range of Lorentz factors [65], implying that, for each beamed source, a few hundred objects not beamed in our direction should exist at the same redshifts.

3.3. Extreme GPS sources

A class of sources that is expected to come out in mm surveys is that of extreme GHz Peaked Spectrum (GPS) or very high frequency peakers. GPS sources are powerful ($\log P_{1.4\,\mathrm{GHz}} \gtrsim 25\,\mathrm{W\,Hz}^{-1}$), compact ($\lesssim 1\,\mathrm{kpc}$) radio sources with a convex spectrum peaking at GHz frequencies. They are identified with both galaxies and quasars. However, unification models by which the two populations differ only by effect of different orientations do not seem to apply in this case. Rather, GPS galaxies and quasars appear to be unrelated populations. They have different redshift, rest-frame frequency, linear size and radio morphology distributions [87, 88, 86, 83]. Also, significantly different evolutionary properties are indicated [24].

Sources peaking above $\simeq 10\,\mathrm{GHz}$ (in the observer's frame) are strongly under-represented in the present samples because they are relatively weak at the frequencies ($\leq 5\,\mathrm{GHz}$) where large area surveys are available. Still, some tens such sources are known [30, 31, 19, 40, 95, 94, 42]. Grainge & Edge [40] report the detection of 50 GPS sources with spectra still rising above 10 GHz (although few details on the survey are given and the source list is not provided); one of these has the emission peak above 190 GHz in the rest frame.

It is now widely agreed that GPS sources correspond to the early stages of the evolution of powerful radio sources, when the radio emitting region grows and expands within the interstellar medium of the host galaxy, before plunging in the intergalactic medium and becoming an extended radio source [33, 73, 8, 84]. Conclusive evidence that these sources are young came from measurements of propagation velocities. Velocities of up to $\simeq 0.4c$ were measured, implying dynamical ages $\sim 10^3$ years [63, 64, 72, 91, 96]. Estimates of radiative ages of small radio sources are also consistent young ages [55]. The identification and investigation of these sources is therefore a key element in the study of the early evolution of radio-loud AGNs.

There is a clear anti-correlation between the peak (turnover) frequency and the projected linear size of GPS sources (and of compact steep-spectrum sources; [34, 60]), suggesting that the process (probably synchrotron self-absorption, although free-free absorption is also a possibility, cf. [10]) responsible for the turnover depends simply on the source size. Although this anti-correlation does not necessarily define the evolutionary track, a decrease of the peak frequency as the emitting blob expands is indicated. Thus millimeter-wave surveys may be able to detect these sources very close to the moment (perhaps within the first years) when they turn on.

On the other hand, it is not clear at this stage whether there is a continuity between low-frequency peaked and very high-frequency peaked GPS sources. The new samples provided by mm surveys and follow-up VLBI observations of extreme GPS sources will allow us to test these ideas. Millimetric surveys might also test the frequency of occurrence of transitions from GPS to blazar spectra, as observed for the quasar PKS0528+134 [102], and allow us to investigate the nature of processes involved.

The self-similar evolution models by [33, 8] imply that the radio power drops as the source expands, so that GPS's evolve into lower luminosity radio sources. With a suitable choice of the parameters, this kind of models may account for the observed counts, redshift and peak frequency distributions of the currently available samples [24]. On the other hand, [84] support a scenario whereby the luminosity of GPS sources *increases* with time (while the peak frequency decreases) until a linear size $\simeq 1\,\mathrm{kpc}$ is reached, and decreases subsequently. This scenario is consistent with the observed positive correlation between $S_{\rm peak}$ and angular size, although it should be noticed that this property refers to the source population and does not necessarily reflect the evolution of individual sources. The present data are insufficient to conclusively prove/disprove either scenario. However the two scenarios yield widely different predictions for counts of GPS sources at mm wavelengths: the first one implies that GPS sources may comprise a quite significant fraction of bright ($S > 1\,\mathrm{Jy}$) radio sources at $\nu > 30\,\mathrm{GHz}$, while very few bright GPS sources are expected at high frequencies in the framework of the second scenario. Bright large area mm surveys will therefore allow us to clearly discriminate among them.

It is often stated in the literature that GPS sources hardly show any variability [59, 52]. However, systematic studies are still lacking. The preliminary results of the study of a complete sample, reported by [85], indicate low variability for GPS galaxies, while GPS quasars are found to vary as strongly as compact flat-spectrum quasars. The GPS quasars monitored by [94] do show strong variability. Since we are dealing with very compact sources (the expected linear size of sources peaking at $\sim 100\,\mathrm{GHz}$ is $\lesssim 1\,\mathrm{pc}$) the relevant timescales are of the order of months to years.

Another interesting issue is polarization of GPS sources. Despite the fact that synchrotron emission is intrinsically polarized up to $\sim 75\%$, very low polarization is seen at cm wavelengths ($\sim 0.2\%$ at 6 cm; [61, 3, 87]). At least in some cases (particularly for GPS quasars), these low polarizations may be attributed, to a large extent, to Faraday depolarization ([59] and references therein). Very large Rotation Measures (RM $\gtrsim 1000\,\mathrm{rad\,m^{-2}}$) have indeed been found [47, 2, 90, 45]. Peck & Taylor [66] find, for a sample of Compact Sym-

metric Objects, limits on the polarization degree at 8.4 GHz with a milliarcsec (mas) resolution of less than 1%. In order to depolarize the synchrotron emission to the observed level, Faraday RMs must reach really extreme values ($\gtrsim 5 \times 10^5\,\mathrm{rad\,m^{-2}}$) or, alternatively, the magnetic field in the circumnuclear region has to be tangled on scales smaller than 1 mas to produce gradients of $1000\,\mathrm{rad\,m^{-2}\,mas^{-1}}$ or more. There are also GPS sources with small measured values of RM.

Similarly large values of RM ($\gtrsim 1000\,\mathrm{rad\,m^{-2}}$) are found for only another class of extragalactic radio sources, namely radio galaxies at the centers of cluster cooling flows [67, 90, 37]. This raises the question of whether GPS sources with high RM are also in cooling flow clusters or whether the high RMs are produced in some other way.

3.4. Low radiative efficiency accretion onto super-massive black holes

Millimeter-wave observations are also crucial to investigate late stages of the AGN evolution, characterized by low radiation efficiency. This matter was recently brought into sharper focus by the discovery of ubiquitous, moderate luminosity (10^{40}–$10^{42}\,\mathrm{erg\,s^{-1}}$) hard X-ray emission from nearby ellipticals. VLA studies at high radio frequencies (up to 43 GHz) have shown, albeit for a limited sample of objects, that all of the observed compact cores of elliptical and S0 galaxies have spectra rising up to $\simeq$ 20–30 GHz [26].

There is growing evidence that essentially all massive ellipticals host black holes with masses 10^8–$10^{10}\,\mathrm{M_\odot}$ (see, e.g., [48]). Yet, nuclear activity is not observed at the level expected from Bondi's [13] spherical accretion theory, in the presence of extensive hot gaseous halos, and for the usually assumed radiative efficiency $\sim 10\%$ [26]. However, as proposed by [74], the final stages of accretion in elliptical galaxies may occur via rotating accretion flows (Advection-Dominated Accretion Flows, ADAFs), characterized by a very low radiative efficiency [32]. The ADAF scenario implies strongly self-absorbed thermal cyclo-synchrotron emission due to a near equipartition magnetic field in the inner parts of the accretion flows, most easily detected at cm to mm wavelengths.

However the ADAF scenario is not the only possible explanation of the data, and is not problem-free. Chandra observations of Sgr A, at the Galactic Center, are suggestive of a considerably lower, compared to Bondi's, accretion rate [4], so that the very low ADAF radiative efficiency may not be required. Also [26, 25] found that the high frequency nuclear radio emission of a number of nearby early-type galaxies is substantially below the predictions of standard ADAF models. They conclude that, to reconcile the advection-dominated scenario with observations, the radio emission from the inner regions must be strongly suppressed, due perhaps to outflows or jets that dump significant amounts of energy into the medium close to the accretion radius, thereby reducing the accretion rates. In fact, it was pointed out by [12, 56] that when the radiative efficiency is very low, a large fraction of the plasma in an advection-dominated inflow/outflow solution (ADIOS) may be unbound, leading to significant winds. Both the intensity and the peak of the radio emission depend on the mass loss rate. The data on sources observed so far indicate peak frequencies in the mm region. Therefore, measurements in this region allow very effective tests of the physics of low-radiative-efficiency accretion.

Perna & Di Matteo [68] estimated that at $\simeq 30\,$GHz the counts of advection-dominated sources can be comparable to the total counts of radio sources estimated by [92] and may be up to a factor of 10 higher if a large fraction ($F \gtrsim 50\%$) of such sources have the radio luminosity predicted by standard ADAF models, without outflows. Although the counts by [89] already rule out large values of F, much tighter constraints will come from counts in the millimeter region, which are even more critically dependent on the fraction of standard ADAF sources since the emission peak shifts from wavelengths $\lesssim 1\,$mm to wavelengths $\gtrsim 1\,$cm when we move from standard ADAF models (no outflow) to models with strong outflows.

The radio emission was found to be correlated with the mass of the central BH [36, 77]; thus a millimeter survey would also provide an estimate of the BH mass function. Improved estimates can be obtained combining radio and X-ray measurements [101].

3.5. AGNs with high frequency free-free self absorption cutoffs.

Free-free absorption cutoffs at frequencies $> 10\,$GHz are expected, in the framework of the standard torus scenario for type 1 and type 2 AGNs, for radio cores seen edge on, and may have been observed in some cases [7]. Again, high radio frequency observations are essential for a comprehensive investigation on these sources.

3.6. Radio afterglows of gamma-ray bursts (GRBs)

The afterglow emission of GRBs can be modelled as synchrotron emission from a decelerating blast wave in an ambient medium, plausibly the interstellar medium of the host galaxy [98, 99, 53]. The radio flux, above the self-absorption break occurring at $\lesssim 5\,$GHz, is proportional to $\nu^{1/3}$ up to a peak frequency that decreases with time. The counts of GRB afterglows at various frequencies have been estimated by [17] (see also [79]). As illustrated by Fig. 1, a large area ($> 10^3\,\mathrm{deg}^2$) millimetric survey to a flux limit $\lesssim 1\,$mJy might discover some GRB. Although, according to [17], GRB counts would be substantially higher at cm wavelengths, higher frequencies are more favorable to pick up the early phases of the GRB evolution.

4. Dusty galaxies

As we move to fainter flux densities, the counts are dominated by a very different population, i.e. galaxies with extreme star formation activity, up to $10^3\,M_\odot$/year, and a different emission process, namely dust re-radiation. It is now clear that a large fraction, or even most, of star formation, is heavily obscured by dust, so that mm/sub-mm surveys provide crucial pieces of information on the early evolution of galaxies.

Furthermore, surveys at these wavelengths are optimally suited for studying the early evolutionary stages of galaxies, as the result of a number of concurrent factors. First, at mm wavelengths local galaxies are very dim; this is true even for star-burst galaxies and even more for normal spirals (the radio emission is

proportional to the star-formation rate) and for radio-quiet ellipticals. Second, spheroidal components of galaxies must have strongly evolved in this band: their dust emission must have been far higher during the phases when they formed their stars. Third, the effect of the strong luminosity evolution is further boosted by the effect of the strongly negative K-correction.

These effects concur to produce the very steep counts, determined by SCUBA and, more recently, by MAMBO (the Max-Planck mm bolometer array at the IRAM 30m telescope) surveys. Surveys at relatively longer wavelengths (mm vs sub-mm) are advantageous for picking up very high redshift forming galaxies, whose observed dust emission at sub-mm wavelengths may come from frequencies beyond the dust emission peak.

Understanding the physical and evolutionary properties of these sources is still a major challenge. Even the best semi-analytic models [18, 23] hinging upon the standard picture for structure formation in the framework of the hierarchical clustering paradigm, tuned to agree with detailed numerical simulations, are stubbornly unable to account for the (sub)-mm counts of galaxies. In fact, the canonical hierarchical clustering models for the formation of galaxies rather predicted that most star formation in the universe occurred within relatively small proto-galaxies, at typical rates of $10\,M_{\odot}$/year, that later merged to form larger galaxies. The data are more consistent with the traditional "monolithic" approach whereby giant ellipticals were already present at substantial redshifts ($z \gtrsim 2$), and formed most of their stars in a single gigantic starburst, followed by essentially passive evolution. The "monolithic" approach, however, is inadequate to the extent that it cannot be fitted in a consistent scenario for structure formation from primordial density fluctuations.

A possible way out was proposed by [41] who elaborated a scheme whereby the early evolution of giant ellipticals is tightly inter-related with that of quasars (see also [29, 80]), and feed-back effects, from supernova explosions and from active nuclei, delay the collapse of baryons in smaller clumps while large ellipticals form their stars as soon as their potential wells are in place, so that the canonical hierarchical CDM scheme – small clumps collapse first – is reversed for baryons. The counts predicted by this model are shown and compared with SCUBA and MAMBO data in Fig. 1.

This scheme entails a number quantitative, testable predictions, in particular about the clustering and gravitational lensing of forming spheroidal galaxies. SCUBA/MAMBO galaxies are expected to be highly biased tracers of the dark matter distribution and therefore strongly clustered. Their clustering properties are indicative of their halo masses. Recent results by [51, 70] show that the model predictions are nicely consistent with the (still limited) data. The estimated $w(\theta)$ for bright SCUBA galaxies [78] and for EROs [20, 21, 22] indicate dark halo masses $\sim 10^{13}\,\mathrm{M}_{\odot}$ for these sources; the $w(\theta)$ for LBGs [38] indicate typical masses at least 10 times lower (see also [54]).

Also, the bright tail of mm/sub-mm counts of forming spheroids is predicted to be strongly affected by gravitational lensing. In fact, although the probability of strong lensing is very small, it has a power-law tail ($p(A) \propto A^{-3}$) extending up to large values. Thus, if counts are steep enough, the fraction of lensed sources at bright fluxes may be large. The mm/sub-mm region is ideally suited for detecting them because, on one side, high redshift sources (with high-

est probability of being gravitationally lensed) are greatly emphasized by steep, negative K-correction plus evolution, and, on the other side, the model by [41] predicts extremely steep counts, reflecting the exponential decline of the Press-Schechter mass function (there are no low-z counterparts to forming spheroids: their formation is essentially completed by $z \simeq 2$). Accurate modelling of the lensing effect on counts [69] shows that almost all spheroids detected at $850\,\mu$m flux densities larger than $\sim 60\,$mJy are strongly amplified by gravitational lensing. Even accounting for all the contributing populations, the fraction of lensed objects at $S_{850\mu\mathrm{m}} \sim 70\,$mJy should remain at the level of about 40% [70].

5. Sunyaev-Zeldovich (SZ) effect from quasar-driven blast waves

We end in a somewhat more speculative vein, introducing a population of sources that may really be yet to be discovered. It is natural to expect that extremely powerful sources, such as quasars, strongly affect the surrounding medium (e.g., they may photo-ionize the intergalactic medium (IGM) [75]). The idea of strong shock heating of the medium by energetic outflows from early quasars, originally developed by [44], has been recently revived by [58, 57, 1]. The main weakness of these analyses is the lack of a convincing physical mechanism or of empirical evidence that a significant fraction of the power generated by quasars comes out as supersonic winds (except in the case of BAL quasars) and goes into heating of the medium. Recent analyses suggest, however, that quasars are the best candidates for accounting for the pre-heating of gas in groups and clusters of galaxies [5, 15]: it is enough that 1–5% of the bolometric emission of the quasars goes into heating of the IGM. But then [71] the heated gas within the host galaxy produces a SZ effect of amplitude (in the Rayleigh-Jeans region)

$$\left|\left(\frac{\Delta T}{T}\right)_{\mathrm{RJ}}\right| = \frac{1}{2}\frac{\Delta\epsilon}{\epsilon_{\mathrm{CMB}}}$$

with $\Delta\epsilon = f_h(E_{\mathrm{bol}}/V)(t_{\mathrm{bw}}/t_c)$, where f_h is the fraction of the total energy (E_{bol}) emitted by the quasar going into heating of the ambient medium, t_{bw} is the lifetime of the blast-wave, V is the volume occupied by the heated gas, and t_c is its Compton cooling time. For $t_{\mathrm{bw}} \simeq t_{\mathrm{exp}}$ (t_{exp} being the expansion timescale) we have

$$\left|\left(\frac{\Delta T}{T}\right)_{\mathrm{RJ}}\right| \simeq 3.4\times 10^{-4}\frac{f_h}{0.01}\frac{E_{\mathrm{bol}}}{10^{62}\mathrm{erg\,s^{-1}}}\frac{\mathrm{Mpc}^3}{V}\frac{50}{H_0}(1+z)^{-3/2}$$

on an angular scale $\theta \sim 100" R(\mathrm{Mpc})$ for $z \gtrsim 1$ ($R \simeq v_{\mathrm{bw}}t_{\mathrm{bw}}$, v_{bw} being the outward velocity of the shocked shell). These figures are not far from the results reported by Richards et al. (1997): $|\delta T/T| \sim 10^{-4}$ over an area of $30'' \times 65"$, and by Jones et al. (1997): $|\delta T/T| \sim 1.4\times 10^{-4}$ in a beam of $100'' \times 175"$. Estimates of the counts of such SZ effects have been worked out by [71] who also pointed out that, due to the relatively small angular scale of these signals, they may be swamped by radio and far-IR emissions of galaxies hosting the quasars. Therefore, to detect them, we should take advantage of the frequency region where these sources are weaker, i.e., once again, of the mm to cm range.

6. Conclusions

Sub-millimeter (SCUBA) and millimeter (MAMBO) surveys have played a crucial role in shaping our understanding of early phases of galaxy formation. In fact, they have proven that most of the star-light at high redshifts ($z \gtrsim 2$) has been reprocessed by dust so that the optical view of the cosmic star-formation history is highly incomplete and biased. On the other hand, such surveys have covered only small areas: from $\sim 0.1\,\mathrm{deg}^2$ for the shallowest ones (flux limit $\lesssim 10\,\mathrm{mJy}$; [78, 14, 16, 9]), to $\sim 0.01\,\mathrm{deg}^2$ for the deep ones [81, 43, 11, 6]. Redshift estimates (e.g. [27]) indicate that many (most?) of the detected sources are likely at substantial redshifts ($z \gtrsim 2$) and correspond to extreme star-formation activity (up to $> 10^3\,\mathrm{M}_\odot\,\mathrm{yr}^{-1}$). Much more extensive surveys are necessary to adequately sample the mm/sub-mm luminosity function of star-forming galaxies. Larger area surveys would also allow us to assess the clustering properties of these sources [51, 70], which provide unique information on masses of the associated dark halos and, correspondingly, crucial tests for scenarios for the formation of structures. As discussed by [69, 70], quite a significant number of high-redshift forming spheroidal galaxies are expected at relatively bright fluxes (above several tens of mJy at $\lambda \sim 1\,\mathrm{mm}$) due to strong gravitational lensing. Detection of these sources would offer a precious opportunity for investigating their properties and to learn about the distribution of matter in the high-z universe.

At somewhat longer wavelengths radio galaxies play an increasingly important role. Surveys at mm to few-cm wavelengths will provide key information on the physical properties of "standard" steep- and flat-spectrum sources and will allow comprehensive investigations of rare, but very interesting, populations of sources with "non-standard" spectra, rising with increasing frequency or keeping flat up to very high frequencies. Such classes of sources are very difficult to single out at low frequencies where they are swamped by the much more numerous "standard" populations. Important examples are blazars, GPS sources, and ADAF/ADIOS sources. Among the many very interesting issues on blazars that can be addressed there are the relationships among the different sub-classes (high- and low-polarization, high- and low-frequency peaked BL Lacs) and the understanding of their variability properties, in particular of intraday variability. Also, thanks to their strong Doppler boosting, blazars can be seen at relatively bright flux densities up to very high redshifts, thus offering a precious opportunity to investigate the presence of super-massive black holes at early epochs and the origin of the radio phenomenon.

Both the earliest and the latest phases of nuclear activity show up most clearly at mm wavelengths. On one side, extreme GPS sources, whose spectra peak at mm wavelengths, probably correspond to the very earliest phases of the evolution of radio sources (perhaps within the first years). Current evolutionary scenarios predict widely different luminosities for these sources, so that mm surveys can easily discriminate among them.

Also the latest phases of the evolution of active nuclei, characterized by low accretion rates and/or low radiative efficiency (ADAF/ADIOS models), show inverted radio spectra, with turnover frequencies in the millimeter range. According to some models the turnover frequency is related to the rate of mass loss

on outflows. The counts of such sources at mm wavelengths are highly sensitive to the accretion/outflow rates.

Yet another class of extragalactic sources with inverted radio emission spectrum are afterglows of gamma-ray bursts. Although they are generally quite faint, some may be discovered by mm surveys covering areas $\gtrsim 10^3\,\mathrm{deg}^3$ to a flux limit $\lesssim 1\,\mathrm{mJy}$. Again, the mm selection picks up very early phases of their evolution.

The above are just examples. It is quite likely that, in addition to the many other areas of scientific interest that may be added, unexpected phenomena will show up as this band opens to surveys.

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